

**Ganymede Grooved Terrain at the Local Scale: Results from Galileo.** R. T. Pappalardo<sup>1</sup>, J. W. Head<sup>1</sup>, G. C. Collins<sup>1</sup>, R. Greeley<sup>2</sup>, and The Galileo SSI Team, <sup>1</sup>Brown Univ. (Geol. Scis., Box 1846, Providence, RI 02912; pappalardo@brown.edu), <sup>2</sup>Arizona State Univ. (Geology Dept., Box 871404, Tempe, AZ 85287).

A primary objective of the Galileo SSI experiment is to elucidate the origin of Ganymede's bright grooved terrain, and this was a focus of high resolution imaging during the first two close encounters with Ganymede (orbits G1 and G2). Companion abstracts by Pappalardo et al. and Head et al. [this volume] summarize the objectives of grooved terrain imaging and provide overview descriptions and interpretations of the primary Ganymede targets on these first two orbits. Results for grooved terrain are summarized here and synthesized with common themes that are emerging from Galileo regarding the origin and evolution of grooved terrain on Ganymede.

**Summary and Interpretations of Galileo High Resolution Observations.** The primary G1 and G2 high resolution targets which address the issue of grooved terrain origin and evolution are: G1 Uruk Sulcus (~75 m/pxl), G2 Uruk Sulcus stereo (~45 m/pxl), G2 transitional terrain (~190 m/pxl), G2 Nippur Sulcus (~100 m/pxl), G2 Marius Regio groove lane (~86 m/pxl), G2 high latitude light/dark boundary (~45 m/pxl), and G1 very high resolution bright terrain (~11 m/pxl). Relevant planning and Galileo images may be seen at <http://www.jpl.nasa.gov/galileo/sepo/atjup/ganymede/ganymede.html>.

**Uruk Sulcus.** Considerations of resolution, viewing geometry, low image compression, and complementary stereo imaging make the Uruk Sulcus region extremely informative [Pappalardo et al., this volume]. Contrast variations in the Uruk Sulcus images are extreme. G2 stereo imaging demonstrates that albedo variations are controlled by topography (e.g. small-scale albedo striping defines ridges and troughs, and dark material appears to collect in topographic lows); thus, landform morphology and structure can be recognized under conditions of high solar illumination. Ridges and grooves are ubiquitous in the Uruk Sulcus region. Distinct geological units with recognizable cross-cutting relationships are apparent, and differences in crater densities demonstrate differences in their relative ages. There is little direct evidence for cryovolcanic resurfacing in this region; instead tectonism appears to be the dominant resurfacing process, capable of resetting the surface age of terrain units [Head et al., this volume]. Visually, ridges show a bimodal distribution of spacings of about 450 and 900 meters, an order of magnitude smaller than Voyager estimates. Fourier analysis of a representative groove lane show that it is actually comprised of dominant wavelengths of ~0.7, 1.3, and 1.9 km, which may indicate a mixing of faulting styles or imbrication of large scale fault blocks into smaller scale blocks [Sun et al., this volume]. Digital elevation models constructed from stereo images indicate a broad wavelength of deformation [Giese et al., this volume] that corresponds to the Voyager-observed topography. This broad scale of deformation may have an origin by necking of Ganymede's lithosphere [Collins et al., this volume], while the finer scale of deformation likely reflects brittle faulting of the surface layer. The stratigraphically lowest and most heavily cratered units [Senske et al., this volume] generally show morphologies indicative of horst and graben style normal faulting. The stratigraphically highest groove lanes exhibit ridges of roughly triangular cross-section, suggesting that tilt-block style normal faulting has shaped grooved terrain, a model supported by relationships at the margins of these groove lanes. En echelon and sigmoidal blocks in some stratigraphically

high units demonstrate that shear has played an important role in shaping this region of grooved terrain. The most recent tectonic episode is interpreted as right-lateral transtension, and this integrated tectonic pattern is superimposed on older units of grooved terrain with N-S and NE-SW tectonic grains. The tectonic style in Uruk Sulcus varies from horst and graben faulting for the oldest grooved terrain units to tilt block normal faulting for the latest units, suggesting an evolution of deformational style with time. Some units in the Uruk Sulcus region which appear relatively smooth in Voyager images are identified in the Galileo images as relatively old, containing subdued ridges and grooves.

**Transitional Terrain.** A range of ridge and trough morphologies and scales are seen across a region transitional from the dark terrain of Marius Regio to the bright grooved terrain of Nippur Sulcus. A shear component is indicated on throughgoing grooves, which appear to grow by linkage of smaller-scale dark terrain fractures. Their orientations likewise imply structural inheritance in the transition from dark to grooved terrain. Evidence here and in the Galileo Regio target region [Prockter et al., this volume] suggests that dark material may be a thin veneer that can shed downslope into topographic lows, leaving high-standing bright material; in this way, tectonism alone can brighten dark terrain to some extent. A bright rhombochasm in the NW corner of the imaged region is interpreted as a pull-apart zone located at the releasing bend of a strike-slip structure, and this bright patch is a good candidate for a site of cryovolcanism of a low viscosity melt. An ~85 x 50 km lozenge-shaped region appears to have rotated in a counterclockwise shear couple; tectonic deformation appears to have brightened this block and its immediate surroundings, perhaps in combination with cryovolcanism.

**Nippur Sulcus.** The Nippur Sulcus target site includes portions of Nippur, Philus, and Elam Sulci. Clear cross-cutting relationships are demonstrated, and the style of tectonism has evidently changed from an early, more regular extensional pattern (Elam and Philus Sulci) to a later pattern of extension and shear (Nippur Sulcus). Philus Sulcus is comprised of parallel lanes of grooved terrain containing component parallel ridges spaced several hundred meters apart. Between the adjacent groove lanes, ridges and troughs have slightly different trends, suggesting formation of each lane with some degree of structural independence. The middle lanes of Philus Sulcus are relatively smooth and may have been cryovolcanically flooded. Graben-like troughs crosscutting the sulcus orthogonally become less distinctive toward the middle lanes, suggesting progressive formation of the middle groove lanes. A shear-like fabric is consistent with right-lateral motion in Philus Sulcus occurring late in its emplacement history. A distinct boundary (likely a fault-bounded depression) marks much of the southern extent of Philus Sulcus where it abuts dark terrain. Dark terrain along the boundary of Philus Sulcus is heavily deformed, and dark terrain structures are abruptly truncated at the boundary. Structural deformation on each side of the boundary suggests a component of horizontal shear along the bounding structure. A bright patch that marks a portion of the boundary adjacent to Nippur Sulcus may be a site of enhanced tectonic deformation, or perhaps localized cryovolcanism. Within Nippur Sulcus proper, en echelon ridges and lensoid/sigmoidal areas imply that

transtension with dextral shear dominated its latter stages of formation. A stratigraphically high strip of light smooth material ~15 km wide alongside Nippur Sulcus is much is characterized by very sharp boundaries. Subdued ridge and trough structure can be seen on its surface. The unit appears to have been tectonically modified but smoothed by subsequent activity, suggesting formation by cryovolcanic flooding.

**Marius Regio Groove Lane.** There is strong evidence that the orientation of a bright grooved lane cutting NW-SE through northern Marius Regio is controlled by pre-existing furrow structure. A set of troughs and fractures trends parallel to the margins of the bright groove lane and the structures therein, and the density of these features appears to be greater toward the groove lane boundary. Along some of its length, the margins of the groove lane are formed by a narrow bounding trough, and this trough appears to be part of a prominent dark terrain furrow system. The terrain within the groove lane consists of a family of grooves subparallel to this trend and may also be controlled by underlying furrow structure. Much of the area between grooves and ridges in the groove lane appears relatively smooth, suggesting cryovolcanic resurfacing.

**High Latitude Light/Dark Boundary.** An ~18 km wide strip of 16 images traverses dark, grooved, and transitional terrains at relatively high northern latitude (centered near 60°N, 170°W). This strip includes a transect of a ~100 km wide portion of an individual sulcus adjoining northwestern Galileo Regio. The constituent ridge and groove topography is likely enhanced by bright frost which concentrates on more northerly facing slopes [Pappalardo et al., this volume]. Grooves trend generally just west of north, and there is some variation in orientation of constituent local-scale groove sets, consistent with a minor oblique component of during extension. If bright frost is present up to the crests of the ridges' northeastern slopes, then the ridges can be interpreted as triangular to somewhat rounded with some being asymmetric in profile. The differing albedos of bright and dark terrain—quite apparent at the Voyager scale—are somewhat obscured by patchy bright material (frost?), but dark terrain is distinguishable by its greater density of large craters and the appearance of a rolling terrain. The transition from grooved to dark terrain is relatively sharp along the eastern boundary of the groove lane, accomplished over a distance of ~2 km. The transition is more gradual along the western edge, marked by a ~5 km wide zone of relatively subdued ridges and grooves. In Voyager images, the terrain southwest of the sulcus is relatively smooth and of intermediate albedo and appears to be transitional from dark to bright terrain [1]. Galileo images show the region has a patchy albedo, with lineations that are bright (likely due to a frost coating and/or shedding of dark material off of steep slopes). Some of the dark terrain lineations have trends similar to the ridges and grooves of the nearby sulcus, suggesting that similar tectonic forces affected the bright and dark regions. The intermediate albedo apparent at Voyager resolution may be an integration of the patchy albedo at high spatial resolution. This patchiness may be due to fracturing of dark terrain and localization of bright and dark deposits, although cryovolcanic and palimpsest-related origins are also being investigated.

**Bright terrain at very high resolution.** Imaging of an unnamed sulcus (proposed name Xibalba Sulcus) at ~11 m/pxl provides important insight into the processes modifying bright terrain at a very small scale [Yingst et al., this volume]. Hill trends and lineaments observed within craters suggest formation of the topography by tectonic extension. No overt evidence for cryovolcanism is observed, suggesting that cryovolcanism has not been

recently dominant at this scale at the imaged location, although it may have played a role in initial emplacement of the higher albedo terrain. The morphology of small-scale features such as massifs suggests modification by some process such as mass wasting, possibly involving local-scale sublimation. If the highest resolution images of Ganymede and Callisto are representative, mass wasting appears to be less significant on Ganymede than on Callisto [Bender et al., this volume].

**Synthesis.** Based on high resolution images of grooved terrain from Galileo's first two orbits, common themes emerge. Ridges and grooves of grooved terrain show morphologies consistent with normal faulting in combination with a minor shear component. In stratigraphically complex regions of grooved terrain, the younger groove lanes exhibit evidence for shear; moreover, younger groove lanes show ridges and troughs with a triangular tilt-block morphology, while older groove lanes exhibit plank-like ridges resembling horsts and graben. Tilt-block style normal faulting implies much greater local strain than does horst and graben faulting, and our preliminary estimates of local strain across these groove lanes is ~50%. Regions that are transitional from dark terrain to bright grooved terrain show abundant evidence for structural control of groove and groove lane orientations by dark terrain fractures and furrows. Some broad sulci are comprised of smaller scale groove lanes that maintain a degree of structural independence and which may form successively. It is probable that tectonic deformation first concentrates along a few prominent structures which in turn propagate deformation into the blocks they define, as regional tensional (or transtensional) straining continues. There is likely long-term activity or reactivation along primary fault structures. Some relatively smooth regions may be cryovolcanic in origin, but definitive evidence for icy volcanism (vents, flow fronts, and clear embayment relationships) has not yet been identified. Normal faulting is the dominant identifiable process in most groove lanes and is capable of tectonically resurfacing groove lanes. Evidence that tectonic modification can brighten dark terrain (e.g. as dark material sheds from steep slopes) lessens the necessary role of cryovolcanism in Ganymede's evolution. The paucity of cryovolcanic features in the G1 and G2 target sites suggests that cryovolcanism may have: a) played a minor role in the history of Ganymede; b) occurred relatively early in Ganymede's history and was largely overprinted by tectonism; and/or c) is intricately interlaced with tectonism, which largely masks its presence. Downslope movement is evident in bright terrain, especially at the small scale, but does not appear to be a dominant process in shaping the morphology of bright grooved terrain. There is no overt evidence for viscous relaxation of small-scale grooved terrain topography.

The emerging Galileo-based model for the origin and evolution of grooved terrain contains elements of previous models [2,3], with important modifications regarding the structural relationships of faults, the timing of faulting, the relative importance of horizontal shear, and the role and timing of cryovolcanism. Observations of grooved terrain planned for future Galileo orbits will further address issues of cryovolcanism, the relationship of tectonism to icy volcanism, and the transition from dark to bright grooved terrain.

[1] Underwood, J.R., et al., Geologic map of the Galileo Regio quadrangle (Jg-3) of Ganymede, in press.  
[2] Golombek, M.P., and M.L. Allison, *GRL* 8, 1139 (1981). [3] Murchie, S.L., et al., *PLPSC 17, JGR* 91, E222 (1986).